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Occurrence of iron in bank filtration wells: case studies in Ituporanga (SC) and Garanhuns (PE)

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ABSTRACT

Bank filtration (BF) is a simplified alternative water treatment, which is the abstraction of water through wells near the banks of surface water located in alluvial aquifers. The chemical composition of the aquifer interferes in the treated water quality by BF technique, and in some cases may promote the appearance of contaminants, such as iron. The objective of this study is to evaluate the occurrence of iron in BF wells in two regions of Brazil, Ituporanga (SC) and Garanhuns (PE), seeking to connect the local conditions to the iron transfer process of soil/subsoil to water. In order to assess the water quality, physical and chemical analyses were performed for raw water, such as the water from the BF wells in both locations. The iron concentration in the water from BF was superior to the surface water in both locations. Although Garanhuns is located in a region with low iron content in the soil, the BF well water showed higher concentrations of this metal than the BF well water in Ituporanga, located in a region with high iron concentrations in the soil. Both sites showed favorable conditions for the transfer of iron present in the soil to the water, through the reduction processes. In Garanhuns, reducing conditions were more intense which allowed for the transfer of a larger amount of iron to the BF water.

Keywords: Water treatment; Bank filtration; Iron

1. Introduction

Bank filtration (BF) is considered as a simplified alternative water treatment of surface waters. In some countries, the technique consists of water abstraction through wells, near the banks of the surface water located in alluvial aquifers or unconsolidated geological formations. Upon pumping the water, the lowering of the water level is induced, causing the surface water (river or lake) to migrate to the well, undergoing a process of filtration through the soil/subsoil during the route [1,2]. Possible contaminants in the surface water are removed en route between the surface water and the well, and retained in the soil sediment [3].

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The efficiency of water treatment for BF depends mainly on the geology of the aquifer, bed composition of the surface water and travel time to the production well. Thus, depending on the soil/subsoil and the final water quality, the BF can be used as the sole treatment or only as pretreatment, requiring additional processing before distribution [4–6].

The chemical composition of the aquifer interferes with the quality of the BF. In some cases, even if there is some removal of contaminants, the emergence of others may occur. Among the most common contaminants found in BF wells, iron and manganese can be noted [1]. The concentration of metals in water, in most cases, is related to the water quality of the surface water and the geology of the soil where it percolates.

The appearance of iron in water from BF wells, due to the solubilization of this element present in the sediments from the aquifer, is an undesirable condition reported in research within the last few years [1,7–12].

The presence of iron in the soil depends mainly on pedogenetic (soil formation process), material of origin and age of the soil. Iron is generally present in the soil in an insoluble form such as ferric oxide, iron hydroxide or iron carbonate. Several factors contribute to the occurrence of iron solubilization, that is, from the insoluble form (Fe^{3+}) to the soluble form (Fe^{2+}), such as a low concentration of dissolved oxygen (DO), high concentration of carbon dioxide or low pH in the middle. The solubilization of iron provides mobility throughout the soil profile, and this element tends to follow the clay in their migration [13–17].

During the course of surface water to the BF well, degradation (oxidation) of organic matter occurs by bacterial action. For the oxidation of the organic material, bacteria primarily use the DO and then the nitrate as an electron acceptor. In the absence of oxygen and nitrate, oxides and iron hydroxides are used as electron acceptors, resulting in the reduction of metal, causing it to dissolve in water. Carrying high concentrations of organic matter in the surface water combined with the geology of the aquifer are contributing factors in the occurrence of iron in BF wells [1,8]. According to Fritzsche et al. [18], iron oxides represent a substantial fraction of secondary minerals and particularly affect the reactive properties of soils and sediments.

Melfi et al. [13] found that iron is present in most of Brazil's soils. The authors conducted a study on the distribution of this element in the soils of Brazil and divided the pedagogical coverage into three major areas: areas with iron content less than 5% (36.2% of the territory), areas with iron content between 5% and 25% (58.8% of the territory) and areas with iron content above 25% (5% of the territory).

The objective of this study is to evaluate the occurrence of iron in the water from BF wells in two regions of Brazil, Ituporanga (SC) and Garanhuns (PE), seeking to correlate the local conditions to the process of transferring iron from the soil/underground to the water.

2. Materials and methods

2.1. Study areas

This paper includes studies conducted in two regions of Brazil (Fig. 1): in the South, in the city of Ituporanga (Santa Catarina), and in the Northeast, in the city of Garanhuns (Pernambuco).

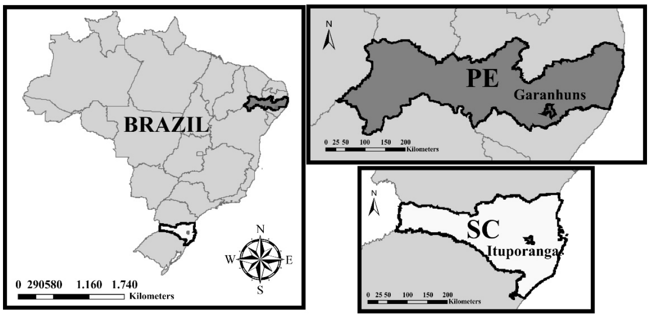

Fig. 1. Location scheme of the municipalities where the BF experiments were performed.

2.1.1. Ituporanga (SC)

The municipality of Ituporanga is situated in the central-eastern region of the state of Santa Catarina, 370 m above sea level. The average annual rainfall ranges from 1,300 to 1,500 mm and the average annual air temperature is 18.5°C [19]. The city is inserted in the Geomorphological Unit of the Itajaí do Sul River, which features extensive flat landings and residual reliefs, bordered by steep steps on cliffs. The geological formation is the Sedimentary Coverage of Gondwana, specifically the Rio do Sul formation (Upper Carboniferous and Lower Permian) which is characterized by shales overlain by a diamictic sandy matrix, fine sandstones, argillites and siltstones. The most common soils in the area are Red-Yellow Podzolic, Cambisol and Low Humic Gley [20]. According to the classification made by Melfi et al. [13], Ituporanga is situated in a region where the soil presents high iron levels (above 25%).

The BF technique was applied in a stretch of the Itajaí do Sul River, the region's main watercourse. The production well was excavated at a distance of 18.5 m from the right bank of the Itajaí do Sul River (Fig. 2). Due to the shallow depth (4.70 m), the well was manually excavated with shovels and lined with concrete rings of 1.0 m diameter. The well was completed with a height of 1.0 m above ground level, in order to protect it from possible flooding.

2.1.2. Garanhuns (PE)

The municipality of Garanhuns is located in the central region of state of Pernambuco, 900 m above sea level. The average annual precipitation is about 874 mm and the average annual air temperature is 20.6°C [21]. The relief in the region consists of hills with rounded shapes, and granite, gneiss and migmatite rocks. The geological formation is Post-Gondwana (Upper Cretaceous) and South American (Cenozoic) [22]. According to the Pernambuco State Soil Code, soil of the region is the type known as Red-Yellow Podzolic or Argisol with a sandy surface coverage and different clay content in the lower layers. According to the classification performed by Melfi et al. [13], the soil of the Garanhuns region presents low iron contents (below 5%).

BF was applied to the Mundaú reservoir, which has a maximum capacity of 1,968,600 m^3, and was built by the

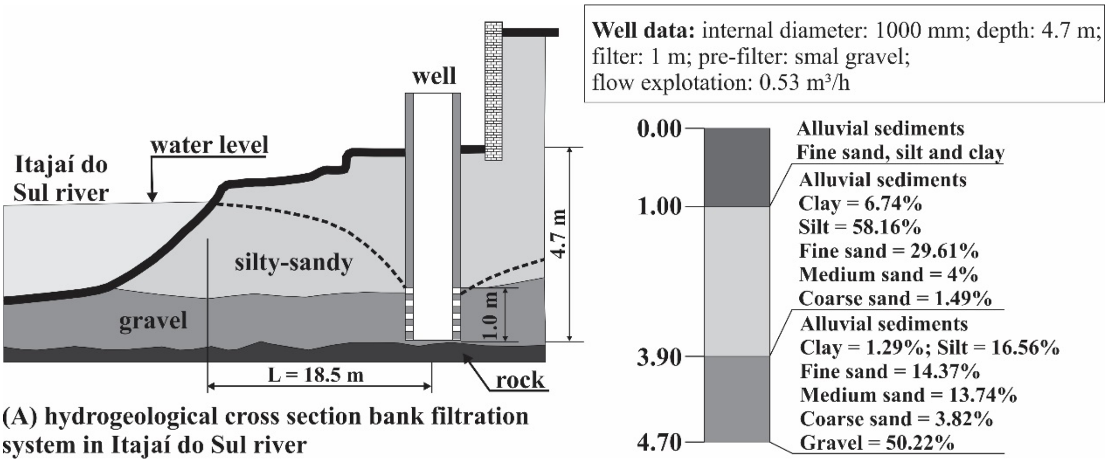

Fig. 2. Bank filtration well section plan (Ituporanga/SC) with details of the sediment layers of subsoil.

National Department of Works against Droughts (DNOCS). Although it was built with the primary purpose of supplying the city of Garanhuns, the Mundaú reservoir receives the domestic sewage of the city, which contributes to the deterioration of the water quality, and it is in an advanced eutrophication stage, which can be observed by constant cyanobacterial blooms [23,24]. The BF production well was implanted downstream from the Mundaú reservoir at a distance of 38.0 m from the base of the embankment dam (Fig. 3).

The production well was excavated to a depth of 2.50 m, covered with a 1.0 m diameter concrete pipe and finished with a 1.0 m height above ground level. Trenches were constructed on the sides of the well in order to capture a greater quantity of water. The trenches were filled with sand of medium to coarse granulometry (diameter ranging from 0.5 to 2.0 mm), and were 1.0 m deep, 10.0 m long and 1.0 m wide (Fig. 4).

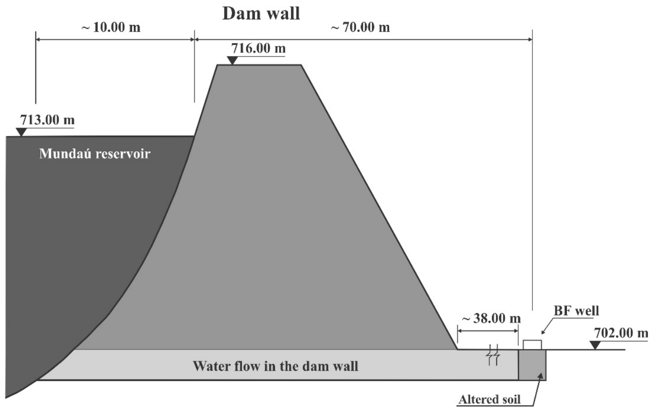

Fig. 3. Section plan of the Mundaú dam and the BF well.

2.2. Physicochemical analysis

Physical and chemical analyses were performed to characterize the raw water (RW) and assess the water quality of the BF. The analyzed parameters follow: pH, DO, turbidity and total iron. The analyses were performed according to the methods stipulated by the Standard Methods for Examination of Water and Wastewater [25].

3. Results and discussion

3.1. Relationship between the quality of raw water and filtered water in bank filtration

The raw water generally shows a significant improvement in its quality as it travels through the bank filter. Table 1 shows that there was improvement in some parameters in both studies, but for other parameters, the surface water did not improve or had its quality deteriorated.

3.2. pH and dissolved oxygen

The pH of the water from the BF well was lower than the raw water in both experiments. In Ituporanga, the pH of the raw water was 6.7, while the bank filtered water was 6.1. In Garanhuns, the difference between the pH of the bank filtered water and raw water was greater, with 6.3 and 8.5, respectively, values. Other authors found the same relationship where the pH of the water from the BF was lower than the surface water [26–29]. The water that percolated through the soil had lowered pH, possibly due to the release of carbon dioxide resulting from the aerobic oxidation process of organic matter.

DO of raw water from the Itajaí do Sul River maintained high values throughout the study period, with a mean of 8.7 mg/L, ranging between 7.9 and 9.8 mg/L. The water from the BF well already had lower values, with an average of 4.0 mg/L, ranging between 3.0 and 4.8 mg/L. The raw water from the Mundaú reservoir averaged 8.2 mg/L, ranging between 5.0 and 13.9 mg/L, the bank filtered water averaged 4.4 mg/L, ranging between 2.0 and 5.1 mg/L. The bank filtered water is likely to have low DO values, since it covers a portion of the aquifer to the production well, the subsurface where there is no exchange of oxygen with the surface and where the degradation reactions of the organic matter that consumes oxygen from the water can occur.

According to Stuyfzand et al. [30], the DO concentration tends to decrease the direction of the surface water to the production well. During the passage of water through the sediment aquifer there is a sudden drop in the concentration of

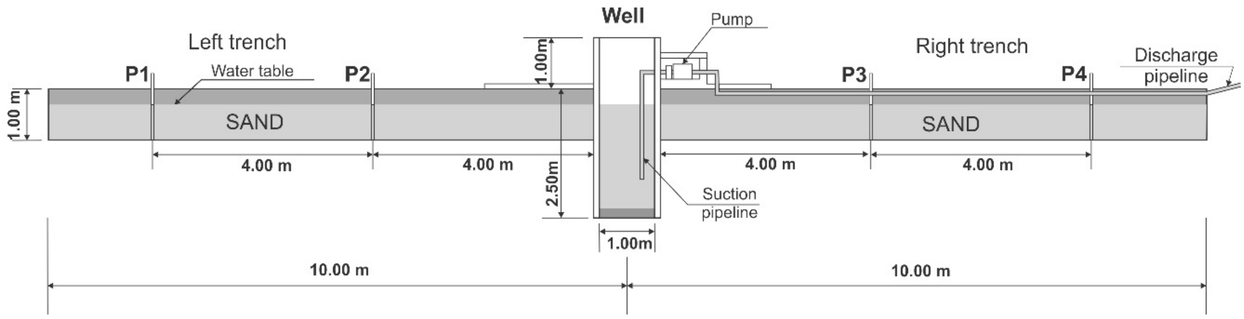

Fig. 4. Detail of the BF well and lateral trenches (Garanhuns/PE).

Table 1
Analysis results of the Itajaí do Sul River, the Mundaú reservoir and the bank filtration wells

Parameters	Itajaí do Sul River						Mundaú Reservoir					
	RW			BF			RW			BF		
	Mean (N = 17)	Range (min–max)	S.D.	Mean (N = 17)	Range (min–max)	S.D.	Mean (N = 12)	Range (min–max)	S.D.	Mean (N = 12)	Range (min–max)	S.D.
pH	6.7	5.0–7.7	0.6	6.1	5.0–6.7	0.5	8.50	7.8 –9.1	0.5	6.3	6.1–6.7	0.2
Dissolved oxygen (mg/L)	8.7	7.9–9.8	0.6	4.0	3.0–4.8	0.4	8.2	5.0–13.9	3.1	4.4	2.0–5.1	1.5
Turbidity (NTU)	32	7.6–58.1	14.8	12.9	2.0–48.3	15.6	44.1	20.2–98.9	23.9	13.3	2.4–20.0	4.9
Total iron (mg/L)	1.0	0.2–2.5	0.6	4.9	0.5–14.5	4.3	0.3	0.2–1.2	0.4	30.1	1.3–47.2	16.9

RW, raw water; BF, bank filtration; S.D., standard deviation.

organic matter and DO from the water. Aerobic microorganisms consume oxygen for degradation of organic matter [7].

The concentration of DO in BF well water is considered as an important factor in the quality of water, because it is directly related to oxidation–reduction processes, the oxidation of organic matter and consequently the reduction of iron compounds [31].

Other studies have identified similar DO behavior, where the DO of the water from surface water was always higher than the BF. This information cooperated with the hypothesis that subsoil water percolation during BF causes a decrease in DO [9,29,32,33].

The low DO values found in the water from BF wells indicate that the subsoil environment tends to have a reducing characteristic which favors the reduction of metal compounds such as iron oxides and hydroxides, and its subsequent solubilization.

3.3. Turbidity and total iron

Turbidity of the water from Itajaí do Sul River remained high during most of the period studied, with an average of 32.0 NTU, ranging from 7.6 to 58.1 NTU. The turbidity of the water from BF remained low during most of the study period, with a mean of 12.9 NTU, ranging from 2.0 to 48.3 NTU, indicating good removal of this parameter (Fig. 5). However, an increase in turbidity of the bank filtered water can be observed from the 14th sampling, which remained high until the end of the study. In two samplings, the turbidity of the water from BF was higher than the surface water.

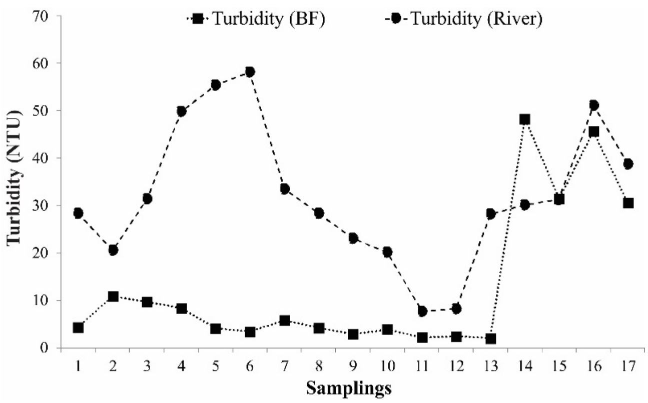

Fig. 5. Variation of turbidity in the water from the Itajaí do Sul River and in the BF water.

The increase in turbidity of the Itajaí do Sul River was possibly due to rainfall in the region, but the increase of turbidity of the BF water coincides with the increase in the total iron in the production well. The precipitated iron provided turbidity to the BF water, which can be seen in Fig. 8.

Turbidity in the Mundaú reservoir remained high throughout the study period, with an average of 44.1 NTU ranging from 20.2 to 98.9 NTU. These high turbidity values found may be related to the high concentration of cyanobacteria present in the reservoir water, as reported by Dantas [23] and Bittencourt-Oliveira et al. [24]. The turbidity of the water from the BF well was 13.3 NTU and had an average ranging from 2.4 to 20.0 NTU (Fig. 6). During most of the study period, the water from the BF well showed values above 10 NTU turbidity, which can be considered high for BF well water. The precipitation of iron present in the BF water throughout the study period, possibly influenced the turbidity values of the water.

Dash et al. [32] conducted BF studies on Lake Nainital (India) and found mean turbidity values in the lake water of 7.1 NTU and the production well mean values were 0.25 NTU, reaching a turbidity removal in the order of 96.5%. Tyagi et al. [27] also conducted BF studies in India, in the Srinagar River and found average values of turbidity in the surface water at 240 NTU, while the turbidity of the water from the BF at 0.8 NTU, showing a removal order of 99.7%. These studies demonstrate that the BF water treatment technique is generally capable of promoting a significant reduction of turbidity when there is no other interference such as iron. In both studies, the water from BF wells presented total iron concentration higher than that of the surface water throughout the study period, indicating that the water that percolated through the soil had increased iron concentration.

One of the limitations of BF is the increase in some ions in the bank filtered water, as is the case of iron, not fitting within the potable water standards [30]. The iron concentration limit in drinking water in Brazil is 0.3 mg/L [34].

Bank filtered water percolates in the subsoil, where predominant conditions such as low DO concentration, high concentration of carbon dioxide gas and low pH favor the solubilization of iron and consequently, the metal in the soil transfers to the water. The low concentration of DO occurs underground, because the DO is consumed in organic matter degradation reactions and also because the subsurface may become saturated with water which prevents gas exchange with the atmosphere. After the DO is consumed, the environment becomes a reducer and microorganisms start to use the electron acceptor compounds available (nitrates, oxides and manganese hydroxides, and iron) that reduce them [1,7,8].

The soil profile is generally divided into horizons (Fig. 7) due to layers of different composition, texture and structure. The most superficial layers (horizons O and A) have more weathered materials and organic waste, since the deeper (horizons C and R) are made of a material slightly modified by weathering. Among these horizons is horizon B, due to the accumulation of materials from the horizon above such as clays, oxides and hydroxides of iron and aluminum [35,36].

In both studies, the wells were drilled at a low depth, 2.50 m in Garanhuns and 4.70m in Ituporanga. Thus, the bank filtered water percolated through the soil of horizon B, which is the layer where there is a predominance of iron and aluminum oxides and hydroxides.

The total iron in the Itajaí do Sul River remained stable during the study period, with an average concentration of 1.0 mg/L, ranging between 0.2 and 2.5 mg/L. The water from BF had an average concentration of 4.9 mg/L, ranging between 0.5 and 14.5 mg/L.

Throughout the study period the total iron concentration from the BF water was higher than the water from the Itajaí do Sul. From the 12th sampling, the total iron concentration in the water from the BF well showed a steady increase until the end of the study (Fig. 8). A few months before this collection, there was an event of heavy rain in the region, where the soil was saturated with water, which certainly contributed to

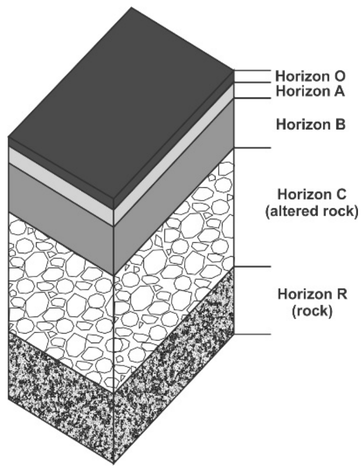

Fig. 7. Characterization of soil horizons (source: adapted from UFRGS [37]).

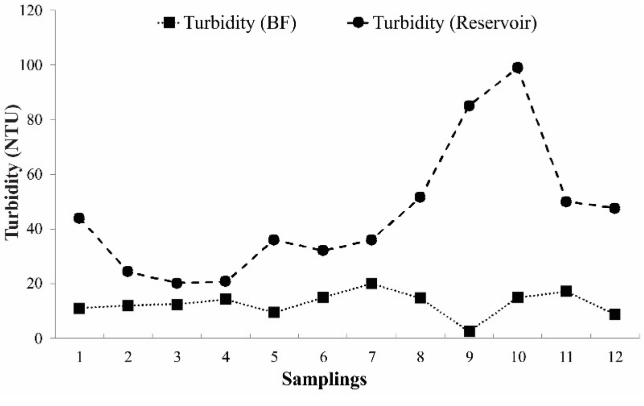

Fig. 6. Variation of turbidity in the water from the Mundaú reservoir and in the BF water.

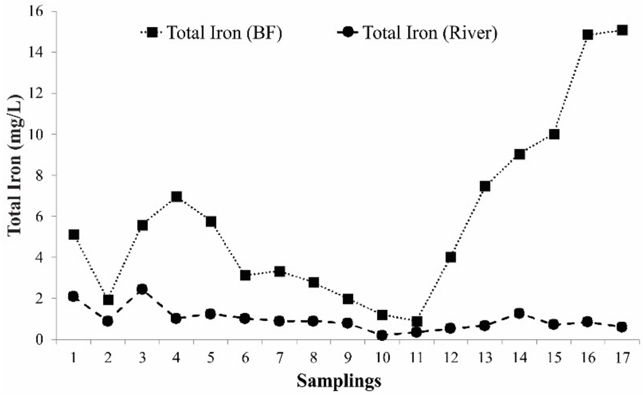

Fig. 8. Variation of total iron concentration in the Itajaí do Sul River water and in the BF water.

making the environment a reducer and consequently influenced iron solubilization and a greater transfer of this element to the water.

The total iron in BF water has no correlation with the total iron in the Itajaí do Sul River, which indicates that the iron in the BF water comes from the soil/subsoil and not the surface water. As previously mentioned, Ituporanga is located in a region with high levels of iron in the soil, which verifies that there was a transfer of this element from the soil to the bank filtered water.

As observed in Fig. 9, the increase of iron in the BF well coincides with the increase of turbidity in the BF water. This indicates that the high turbidity values found are the result of iron precipitation in the BF well water.

In Ituporanga, the collected samples were analyzed after some hours in the laboratory. As the water contained dissolved iron, which is easily oxidized, during the period between collection and analysis, the iron may have been oxidized and precipitated providing increased turbidity in the water.

The total iron concentrations found in certain periods in Ituporanga (SC) were so high that the iron precipitation resulted in complete obstruction of the discharge pipe causing the pump to burn.

The Mundaú reservoir showed low levels of total iron, with an average concentration of 0.3 mg/L, ranging from 0.2 to 1.3 mg/L. Since the water from the BF well showed values of total iron higher than the surface water throughout the study period with an average concentration of 30.1 mg/L and ranging from 1.3 to 47.2 mg/L (Fig. 10).

Although Garanhuns is located in a region with low iron content in the soil, iron concentrations found in the BF well were higher than those found in Ituporanga. What can be attributed to this fact is that reducing conditions were more intense in Garanhuns. The soil downstream from the dam (BF well drilling site) found itself continually saturated due to the water percolation of the dam. As previously mentioned, the Mundaú reservoir received domestic sewage contributions from the municipality and had high cyanobacterial density, which leaves the water with a high concentration of organic matter. The oxidation of organic matter, combined with the soil saturation during percolation of the water through the subsoil, makes it a reducing environment, favoring the reduction of iron and its solubilization. This may explain the reason for the high concentration of total iron found in the water from the BF well in Garanhuns.

The iron concentration was high throughout the study period in the BF well, but turbidity did not follow this variation as noted in the study in Ituporanga. This behavior can be observed in Fig. 11, where the variation of parameters during the study is shown.

The BF water from Ituporanga showed turbidity values of 45 NTU when the total iron concentration was 14.5 mg/L, and in Garanhuns, the maximum turbidity was 20 NTU when the total iron concentration was 43.3 mg/L. This fact can be explained by the collection procedure and analysis of turbidity. In Garanhuns, turbidity was analyzed in the field immediately after collection, thus it did not favor oxidation, and iron precipitation and turbidity values were not significantly altered. The turbidity values in Garanhuns possibly influenced the precipitated iron, but this influence was not intensified as in Ituporanga.

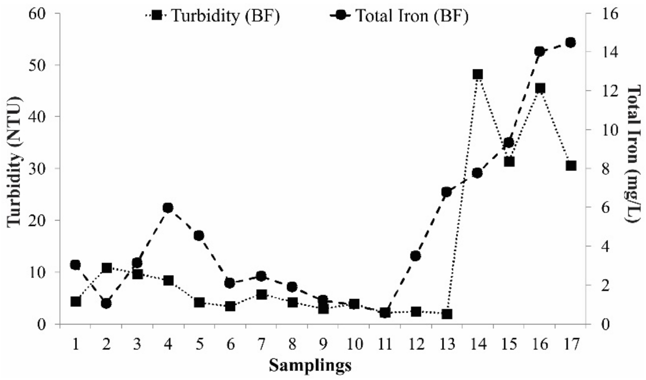

Fig. 9. Variation of the total iron concentration and turbidity in the BF water in Ituporanga (SC).

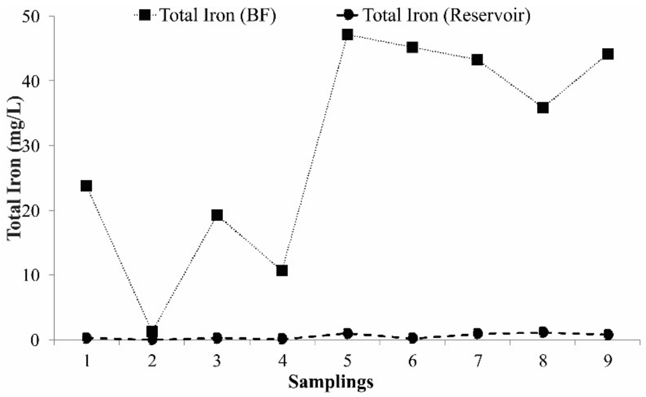

Fig. 10. Variation of total iron concentration in the water from the Mundaú reservoir and in the BF water.

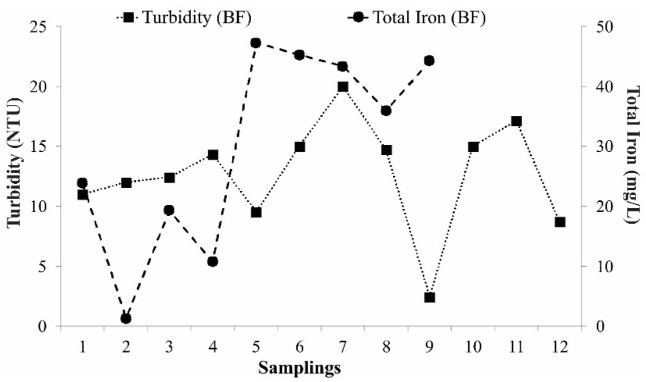

Fig. 11. Variation of the total iron concentration and turbidity in the BF water in Garanhuns (PE).

The iron concentration in the BF well in Garanhuns was very high at certain times of the study. The iron precipitation was evident by the color of the water in the production well and in the same manner as in Ituporanga, the discharge piping in Garanhuns was obstructed by the precipitated iron, which also caused the pump to burn.

Grischek and Paufler [38] observed that high concentrations of iron in BF systems originate from the water present in the aquifer. Plus, after a long period of pumping, the concentration of iron in the water extracted from the well is reduced by the "wash out" effect of the aquifer. The authors also state that one way to avoid high iron concentration in the BF well would be to increase the contribution of the surface water in the bank filtered water, either by approximating the well and the surface water or by increasing the pumping rate.

4. Conclusions

The BF option represents a simplified treatment of drinking water, though depending on the chemical composition of groundwater and the water quality to be treated, the transfer of iron to the bank filtered water can occur, as noted in the studies. The iron transfer process present in the sediment aquifer for the water is related to the redox processes where low DO concentrations favor the reduction of iron and its subsequent solubilization. However, Ituporanga is located in a region where the soil has iron levels higher than those found in Garanhuns. In the latter location, there was a greater iron transfer from the aquifer into the bank filtered water, which attributed to the fact that the reservoir water had a high concentration of organic matter and the location on the outskirts of the production well was constantly saturated with water from the dam, providing an environment with more intense reducing conditions. The relation between turbidity and total iron is subject to the time between collection and analysis, and the longer the period between the collection and analysis of turbidity, the greater the possibility that the dissolved iron will oxidize and precipitate, providing turbid water.

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